GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 17, PAGES 2681-2684, SEPTEMBER 1, 2000

Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations

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Abstract. The Asian summer monsoon response to global warming is investigated by a transient greenhouse warming integration with the ECHAM4/OPYC3 CGCM. It is demonstrated that increases of greenhouse gas concentrations intensify the Asian summer monsoon and its variability. The intensified monsoon results mainly from an enhanced land-sea contrast and a northward shift of the convergence zone. A gradual increase of the monsoon variability is simulated from year 2030 onwards. It seems to be connected with the corresponding increase of the sea surface temperature variability over the tropical Pacific.

Introduction

The Asian monsoon is one of the most influential atmospheric circulations. Summer climate variabilities in Asia are closely related to the variations of the Asian summer monsoon system which is driven mainly by the differential heating of the Indian Ocean and the adjacent Asian landmass, including the snow cover over the Eurasian continent [*Hahn and Shukla,* 1976; *Douville and Royer,* 1996]. Through the Walker circulation, the El Niño/Southern Oscillation (ENSO) also has a considerable impact on the variability of the Asian summer monsoon [*Webster and Yang,* 1992; *Ju and Slingo,* 1995; *Arpe et al.,* 1998]. An active role of the Asian summer monsoon on the intraseasonal and interannual variations of the global climate system has been suggested [*Yasunari,* 1991].

The possible influence of increasing levels of atmospheric trace gases on the Asian monsoon is one of the focuses of some recent studies. For example, observational analysis of *Kumar et al.* [1999] has indicated the role of increased land surface temperature in enhancing the monsoon but weakening the monsoon and ENSO relationship at interannual time scales in recent decades. *Kitoh et al.* [1997] demonstrated a significant increase of the Indian monsoon rainfall due to increased CO_2 in a coupled GCM. Analyzing the NCAR coupled GCM experiment with doubled CO_2 concentration, *Meehl and Washington* [1993] find an intensification of both the Asian summer monsoon and its variability. However, *Lal et al.* [1994] showed only a marginal increase in the Indian monsoon rainfall variability.

Although there has been a series of investigations, it is still not clear how the Asian summer monsoon responds to global warming, especially in transient greenhouse warming experiments. Thus, it is meaningful to study the response of the Asian summer monsoon, including the mean monsoon and its variability, to a gradual increase of the atmospheric CO_2 concentration with a state-of-the-art coupled general circulation model (CGCM).

Model, experiment, and data

The model used in this study is the ECHAM4/OPYC3 CGCM. The atmospheric and land surface components are ECHAM4, which is a spectral model of triangular truncation with total horizontal wavenumber 42 (T42) and with 19 vertical levels. The soil model comprises the budgets of heat and water, the snow pack over land, and the heat budget of land ice. A detailed description of the ECHAM4 model is given by *Roeckner et al.* [1996]. The OGCM component (OPYC3) is developed by *Oberhuber* [1993]. It consists of three submodels; the interior ocean, the surface mixed layer, and the sea ice, respectively. There are 10 interior vertical layers below the surface mixed layer. Fluxes of momentum are unconstrained, while fluxes of heat and fresh water are flux adjusted but only by annual averages. The detailed coupling strategy and technology of ECHAM4 and OPYC3 are described by *Bengtsson* [1996] and *Bacher et al.* [1998].

In the transient greenhouse gas warming (GHG) run, from 1860 to 1990, the changes in the annual concentrations of the greenhouse gases are prescribed as observed and, from 1990 onwards, according to IPCC scenario IS92a [*IPCC,* 1992]. In the control run, the concentration of the greenhouse gases are prescribed according to current conditions [*IPCC,* 1994]. However, the aerosol effect is not included in the runs. Details on the experiments can be found in the work of *Roeckner et al.* [1999]. With these experiments, *Hu et al.* [2000a, 2000b] investigated the impact of global warming on the Asian winter monsoon and on other climate modes,

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Paper number 2000GL011550.
0094-8276/00/2000GL011550$05.00

Timmermann et al. [1999] analyzed the response of ENSO, and *Latif et al.* [2000] studied the impact on the North Atlantic thermohaline circulation. The data used in the present work include monthly means of surface temperature, wind at 850 hPa, total (large-scale and convective) precipitation, and velocity potential at 200 hPa.

Change in mean monsoon

Figure 1 shows the mean total precipitation simulated during 1940-1989 and some difference maps at different stages of the GHG run. Comparing with observations (see Figure 1a in *Kitoh et al.* [1997]), the broad-scale aspects of the Asian monsoon precipitation is reasonably well simulated by the ECHAM4/OPYC3 CGCM, although the precipitation is somewhat underestimated over land and overestimated over the tropical Indian Ocean (*Dümenil,* 1998). The differences in Figure 1 clearly demonstrate the steadily and pronounced enhancement of the Asian summer monsoon precipitation forced by the increase in greenhouse gas concentrations. The pronounced enhancement of precipitation is mainly confined to the Indian peninsula and its vicinity. A broad-scale Asian summer monsoon index is defined as the mean total precipitation in June, July, August, and September averaged in 0~20°N, 40°E~110°E. The time evolution of the index (not shown) indicates that a steady upward trend becomes evident since the 1980s and the precipitation change follows the increase in greenhouse gas concentrations.

The intensified Asian summer monsoon results mainly from the enhanced land-sea contrast, as the land heats up more rapidly than the ocean at the increased greenhouse gas forcing (not shown). The enhanced land-sea temperature contrast leads to enhanced moisture convergence over land. Comparing with present climate (Figure 1a), the tropical convergence zone in the Indian Ocean shifts northward and the moist air transport from the tropics to the south Asian land increases in the warming periods (Figures 1b-1d). The anomalous convergence and divergences regions at 850 hPa are consistent with the precipitation changes (Figure 1b-1d). In addition, the ascending branch of the Walker circulation is shifted westward both in spring and summer by the more rapid heating of the Asian continent, as revealed by the analysis of velocity potential at 200 hPa (not shown).

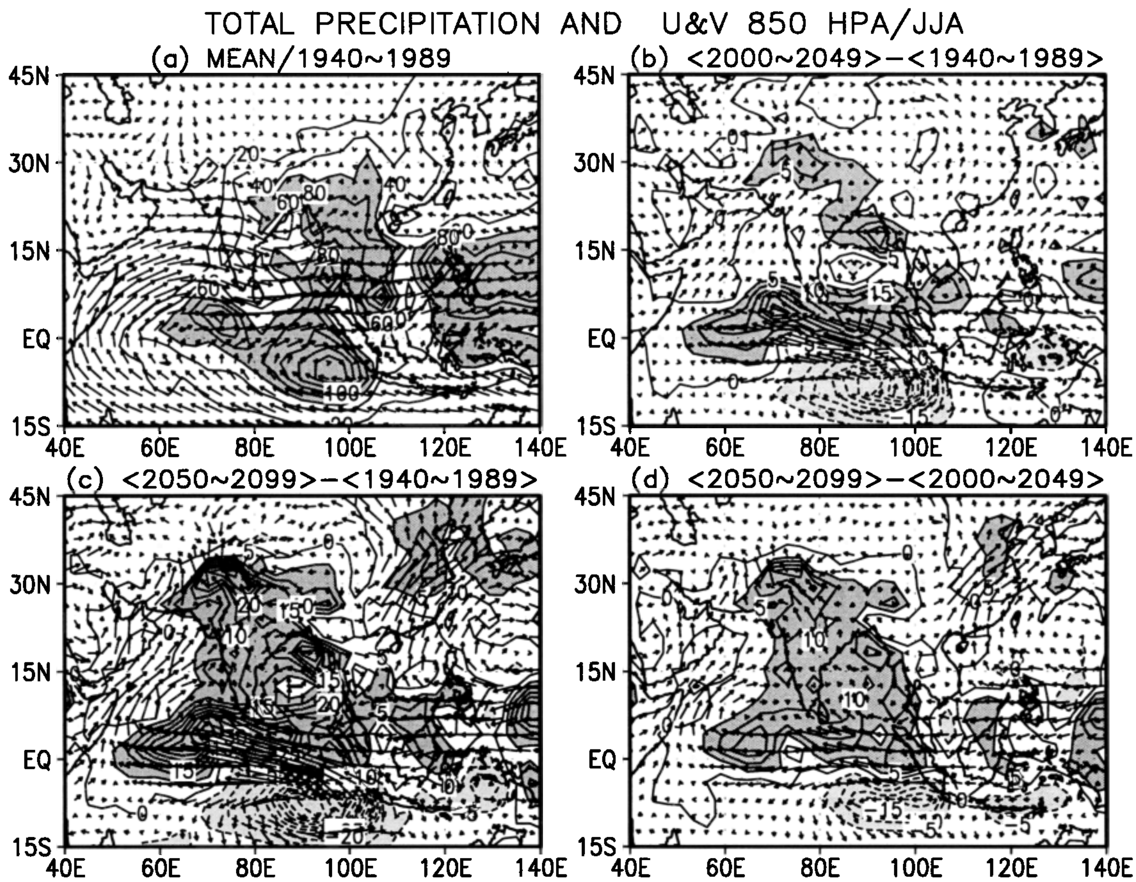

Figure 1. Mean total precipitation (lines and shaded) and the wind field at 850 hPa (vectors) during (a) 1940-1989, and the differences: (b) the mean during 2000-2049 minus Figure 1a, (c) the mean during 2050-2099 minus Figure 1a, and (d) Figures 1c minus 1b. Contour interval is 20 cm in Figure 1a, 5 cm in Figures 1b-1d. Darker (lighter) shading indicates the regions with values greater (less) than 20 (−20) cm in Figure 1a, 5 (−5) cm in Figures 1b-1d. The vectors in Figures 1c-1d are enlarged 6 times referred to that in Figure 1a.

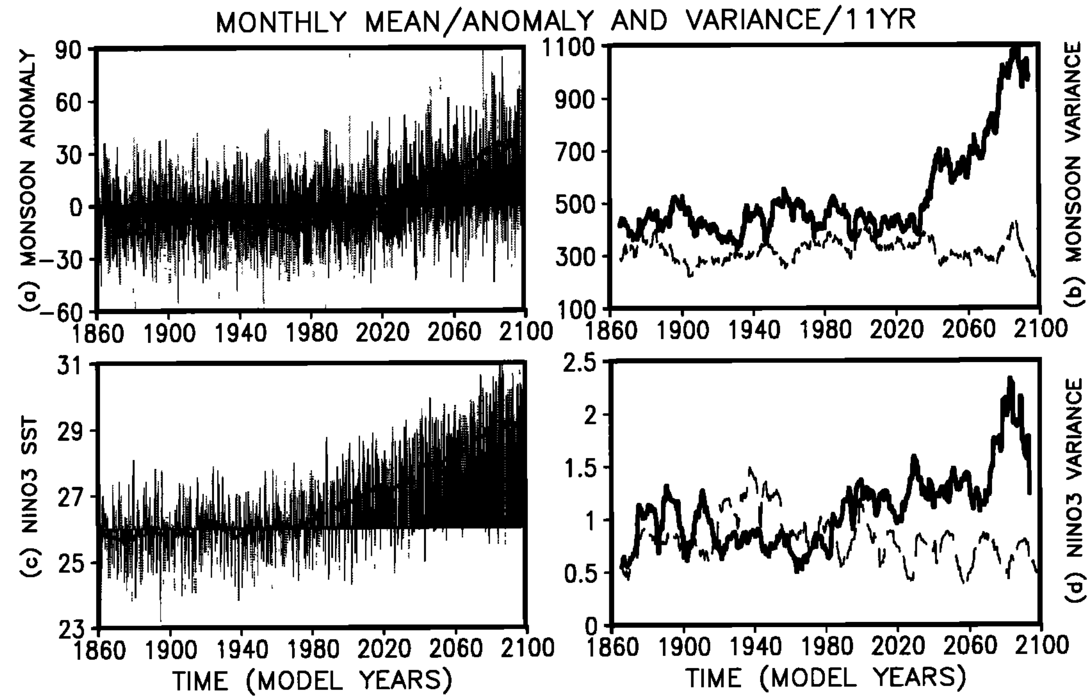

Figure 2. (a): the monthly anomalies of the broad-scale Asian monsoon index (AMI) (bars) and the 11 year runing means (dashed line) in 1860-2099; (b): sliding variances of the AMI using a 11 year window in the GHG (solid line) and control (dashed line) runs; (c) and (d): same as (a) and (b), respectively, but for monthly mean NINO3 (5°S~°N, 150°W~90°W) SST. The anomalies in Figure 2a are the deviations from the climatic monthly mean during 1860-2099. Calculations of the sliding variances are relative to their corresponding running means. The units are mm, $(mm)^2$, °C, and $(°C)^2$ in Figures 2a-2d, respectively.

Change in monsoon variability

Besides the mean monsoon, its variability is another key element in affecting the agriculture, economy, and life in the monsoon regions. From Figures 2a and 2b, it is demonstrated that the monsoon variability increases significantly in the warm climate. The increase becomes significant from year 2030 onwards. Different analyses indicate that the variance evolution patterns are similar when using various high-pass filters and trend deduction methods.

The warming trend of the NINO3 sea surface temperature (SST) becomes pronounced after 1980 (Figure 2c). Figure 2d shows the sliding variances with 11 year window for detrended monthly mean NINO3 SST. The variabilities of the NINO3 SST are enhanced in the warming periods. The increases of the variabilities of the NINO3 SST occur mainly in summer and spring. Analysis of the unforced control experiment shows that the model well simulates the correlations between the NINO3 SST and the Asian summer monsoon (*Dümenil,* 1998). Therefore, it is reasonable to speculate that the relation between the variabilities of the NINO3 SST and the Asian monsoon can be well simulated by the model. Comparing the upward trends of the variabilities in Figures 2b and 2d, it is found that the variance changes are generally coherent during 2030-2099 between the monsoon index and NINO3 SST. Since at the intraseasonal and interannual time scales, the Asian summer monsoon is largely affected by ENSO [*Yasunari,* 1991; *Ju and Slingo,* 1995; *Arpe et al.,* 1998], it seems that the high variance of the monsoon simulated in the warming climate is connected to the corresponding high variances of the NINO3 SST.

Summary and discussion

The Asian summer monsoon response to global warming is investigated by a transient greenhouse warming integration with the ECHAM4/OPYC3 CGCM. It is demonstrated that the increase in greenhouse gas concentrations intensifies the Asian summer monsoon. The intensified monsoon results mainly from the enhanced land-sea contrast of temperature, a northward shift of the convergence zone and a westward shift of the ascending branch of the Walker circulation, as the land heats up more rapidly than the ocean in the GHG run.

Increases in greenhouse gas concentrations enhance also the variability of the Asian monsoon. The increase of the Asian monsoon variability is most pronounced from 2030 onwards. It may be speculated that the increase is somehow related to the corresponding increase of the variance of the NINO3 SST. Some investigations also emphasized the role of mean ocean and atmosphere thermal condition change in the enhancement of the monsoon variability. For example, an observational study showed that increased interannual variability of Indian monsoon precipitation is associated with warmer land and ocean temperatures (not the land-sea thermal contrast) in the monsoon region [*Meehl and Washington,* 1993]. In addition, aerosol can be a very influential factor for the response of the Asian monsoon [*Boucher et al.,* 1998], and the hydrological cycle (soil moisture and snow cover) also plays an important role in the feedback process of the Asian monsoon system [*Zhao and Kellogg,* 1999]. Therefore, the roles of the aerosol and hydrological cycle in the monsoon variability change are open questions. It is also a future topic to compare the present results with the results from various models and global warming scenarios.

Acknowledgments. The authors are grateful to the colleagues at MPI for Meteorology. This work was supported by the European Union through its PROMISE project and National Science Foundation (ATM9907915).

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(Received February 21, 2000; accepted July 17, 2000.)